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UNDERWATER HEARING IN MAN: III. AN INVESTIGATION OF UNDERWATER SOUND LOCALIZATION IN SHALLOW AND NOISY WATER

Paul F. Smith, et al

Naval Submarine Medical Research Laboratory
Groton, Connecticut

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NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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REPORT NUMBER 779

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III. An Investigation of Underwater Sound Localization in Shallow and Noisy Water

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Bureau of Medicine and Surgery, Navy Department
Research Work Unit M4306.03-2090DXC9.02

Released by:

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SUMMARY PAGE

PROBLEM

To determine the ability of underwater swimmers to discriminate the angular separation of sound sources in a noisy, shallow water reverberant environment.

FINDINGS

Divers in a reverberant environment apparently can localize underwater sound sources with a sufficiently high degree of accuracy that investigations into practical acoustic navigational systems appear worthwhile.

APPLICATION

These findings contribute to the determination of the characteristics of underwater hearing in man and toward the development of acoustic navigation aids for Navy divers.

ADMINISTRATIVE INFORMATION

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13 ABSTRACT

The ability of divers to discriminate the angular separation of two sound sources in the presence of high ambient noise in a reverberant environment was tested. In a first experiment it was found that divers could not discriminate directionality with separations as large as 90° for low signal-to-noise ratios. However, when the signal-to-noise ratio was increased to about 19 dB, all four divers could discriminate a 30° angle with 100% accuracy. Two of the four divers could discriminate a 15° separation of sources. In a second experiment a procedure was used in which the angular separation between sound sources could be continuously varied between about 35° and 1.4°. Six divers were tested but the data for one diver was uninterpretable. For the remaining five divers the underwater minimum audible angle for a 46-Hz band of noise centered at 1 kHz varied between 2.7° and 8.6° over all trials. There was some suggestion in the data that experience in underwater listening enhances localization skills.

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ABSTRACT

Tests were made concerning the ability of divers to discriminate the angular separation of two sound sources in the presence of high ambient noise in a reverberant environment. In a first experiment, it was found that divers could not discriminate directionality when separations were as large as 90° for low signal-to-noise ratios. However, when the signal-to-noise ratio was increased to about 19 dB, all four divers could discriminate a 30° angle with 100% accuracy. Two of the four divers could discriminate a 15° separation of sources. In a second experiment, a procedure was used in which the angular separation between sound sources could be continuously varied between about 35° and 1.4°. Six divers were tested, but the data for one diver could not be interpreted. For the remaining five divers the underwater minimum audible angle for a 46-Hz band of noise, centered at 1 kHz, varied between 2.7° and 8.6° over all trials. There was some suggestion in the data that experience in underwater listening enhances localization skills.

UNDERWATER HEARING IN MAN:
III. An Investigation of Underwater Sound Localization in Shallow and Noisy Water

INTRODUCTION

Being able to navigate under water by means of the unaided ear would be a great asset to the Navy diver, since he would not be encumbered by bulky and/or expensive electronic equipment. The ability to navigate by sound would permit a much greater range of activity than is currently thought possible.

Western man has not made extensive use of unaided underwater hearing. Indeed, until recently, it was commonly believed that man under water is deprived of useful hearing. However, there are groups of fishermen in Kelantan and Trengganu, on the east coast of Malaya, who are led by experts called juru sĕlam.[1,2,3] The juru sĕlam dive into the water and listen for fish with the unaided ear. These men are reputed to be able to detect, classify, and locate in azimuth, depth, and distance, schools of fish. Furthermore, they apparently can determine the course a school is making and estimate its size.

Acquiring this skill requires considerable training, and not all trainees become successful juru sĕlam. One juru sĕlam studied the art of fish-listening for two years. He told Firth[1] that it took him about three months to hear the fish noises and to separate them, being unable at first to distinguish fish sounds from the other sounds of the sea.

As stated before, in the Western world it has generally been believed that man was essentially deaf under water. Of those investigators that did show that man could hear under water, the consensus was that underwater hearing was mediated by a bone conduction mechanism, which precluded any possibility of underwater sound localization. E. F. Weber[4] was perhaps the first to assert (in 1851) that the best man could do with his head immersed and his ear canals filled with water was to distinguish sounds coming from the left from those coming from the right. Bauer and Torick[5] argued that directional perception is lost under water partly because of the increased speed of sound in water which reduces interaural time and phase cues, and partly because underwater hearing is, to some extent, bone conduction hearing.

Such arguments let to the conclusion that some sort of hearing aid is required for divers to be able to reliably localize underwater sound sources. Various aids have been proposed ranging from sophisticated electronic instruments[5] to a rather primitive ea trumpet.[6] All such devices are of dubious utility in the light of existing findings.

A detailed review of underwater hearing sensitivity research has been given by Smith[7] with a shorter but updated account being given by Harris[8] in his comprehensive review of hearing in

wet and dry hyperbaric environments. Harris also reviewed recent research on underwater auditory localization.

Research undertaken by Ide during World War II showed that man can hear under water, is able to receive intelligence with the unaided ear, and can, to some extent, navigate with the use of auditory localization.[9] Later researchers[7,8] in more carefully controlled experiments have shown that hearing sensitivity under water is sufficiently acute to enable man to hear not only artificial (man made) noises but some natural noises as well.

Ide found that many divers can be trained to reliably localize sound sources.[9] However, underwater sound localization appeared to be a skill that must be developed and not all divers could acquire this skill in the brief training given. Ide proposed selecting men with an aptitude for underwater direction sensing, and assigning one or two such men to each commando swimming team to serve as navigators for the group as a whole.

Hollien,[10] using a procedure which might have adequately demonstrated that man could not localize sound under water (the expected result), found that, indeed, his subject did perform at above chance levels. This finding led to further experiments which are still in progress at the Communications Sciences Laboratories of the University of Florida. In general, it has been amply demonstrated that man does have some sound localization skills available to him in the underwater anechoic environment.

Feinstein[11] has recently published data showing that man's underwater localization acuity may be comparable to that of some marine mammals. Of course, Feinstein may have been comparing man at his best with the animals at their worst. Nevertheless, and this is the point, he has shown rather convincingly that divers with no sensory aids whatsoever can perform auditory localization tasks under water with some precision. In his study, four divers yielded a mean minimum audible angle (m.a.a.) of 7.3° for a white noise source.

Like Ide and Feinstein,[9,11] Leggiere et al.[12] had some subjects who seemed not to be able to localize underwater sound sources although others of their subjects could do so with considerable accuracy. These latter authors ascribed the lack of localization ability by their nonperforming subjects to probable anxiety reactions. However, the comments of the juru sělam to Firth cited above, and Ide's findings, imply that the auditory cues available for underwater localization of sound sources may be quite subtle, and that there may be (initially) profound differences among men in the ability to utilize these cues. The nature of these cues, and the variables which might identify persons with an aptitude for underwater listening from among the general population, are not understood. The inability of some divers to perform underwater localization tasks without the opportunity for considerable training should not at this time be taken as justification for the development of expensive and/or cumbersome apparatus. Furthermore, researchers in the field are well advised

not to rely on the negative performance of a few unskilled divers, especially if those divers have had little experience in observing in psychoacoustic experiments.

The purpose of the present study was to determine whether sound localization is possible in a noisy and reverberant shallow water environment and to estimate the underwater m.a.a. in such an environment.

Two experiments were conducted. In the first, a procedure was used which permitted a high response rate from the subjects and was capable of yielding evidence that localization in that particular environment might be possible by the subjects at hand. The second experiment, planned to be executed only if the first demonstrated probable localization ability, was much more laborious in that the data yield per unit time was very low. However, with sufficient data, a relatively precise estimate of the underwater m.a.a. could be made.

METHOD

Experiment 1

Subjects. The subjects for the first experiment were four young male undergraduate or graduate students in the School of Oceanography at the University of Rhode Island. All had received diving training at the University and had some open water experience. None had a hearing loss in excess of 20 dB at any important frequency. None had previously participated in a psychophysical experiment.

All divers wore complete wet suits with hoods. There was no standardization of any item of equipment, each diver using his own gear. Most divers wore 1/4" thick neoprene hoods. One man wore two hoods, one 1/8" thick and one about 1/4" thick.

Apparatus. The apparatus for the first experiment is schematized in Fig. 1. White noise from a Grason-Stadler model 445-B noise generator was band limited by an Allison model 2BR band pass filter, divided into two channels and delivered to two Grason-Stradler model 1287 electronic switches which were controlled by Grason-Stradler 1200 series programming modules. The signal was then passed through precision decade attenuators having a resolution of 0.1 dB (Daven type H692-R), and amplified by Macintosh MC2100 power amplifiers which drove two J-9 underwater loudspeakers.

The J-9's were suspended from a framework of 2 X 4's which was lashed to the pilings of a pier. Horizontal members of the framework were marked off so that the J-9's could be set at any of 12 positions, which corresponded to angles of 15° to 90°.

Two underwater switches (W.E.T. model S8) were used by the divers to signal responses. These switches provided inputs to the Grason-Stadler 1200 series control system which tallied responses, initiated successive trials, and terminated blocks after a predetermined number of trials.

A Naval Underwater Systems Center, type XU1295, calibrated hydrophone

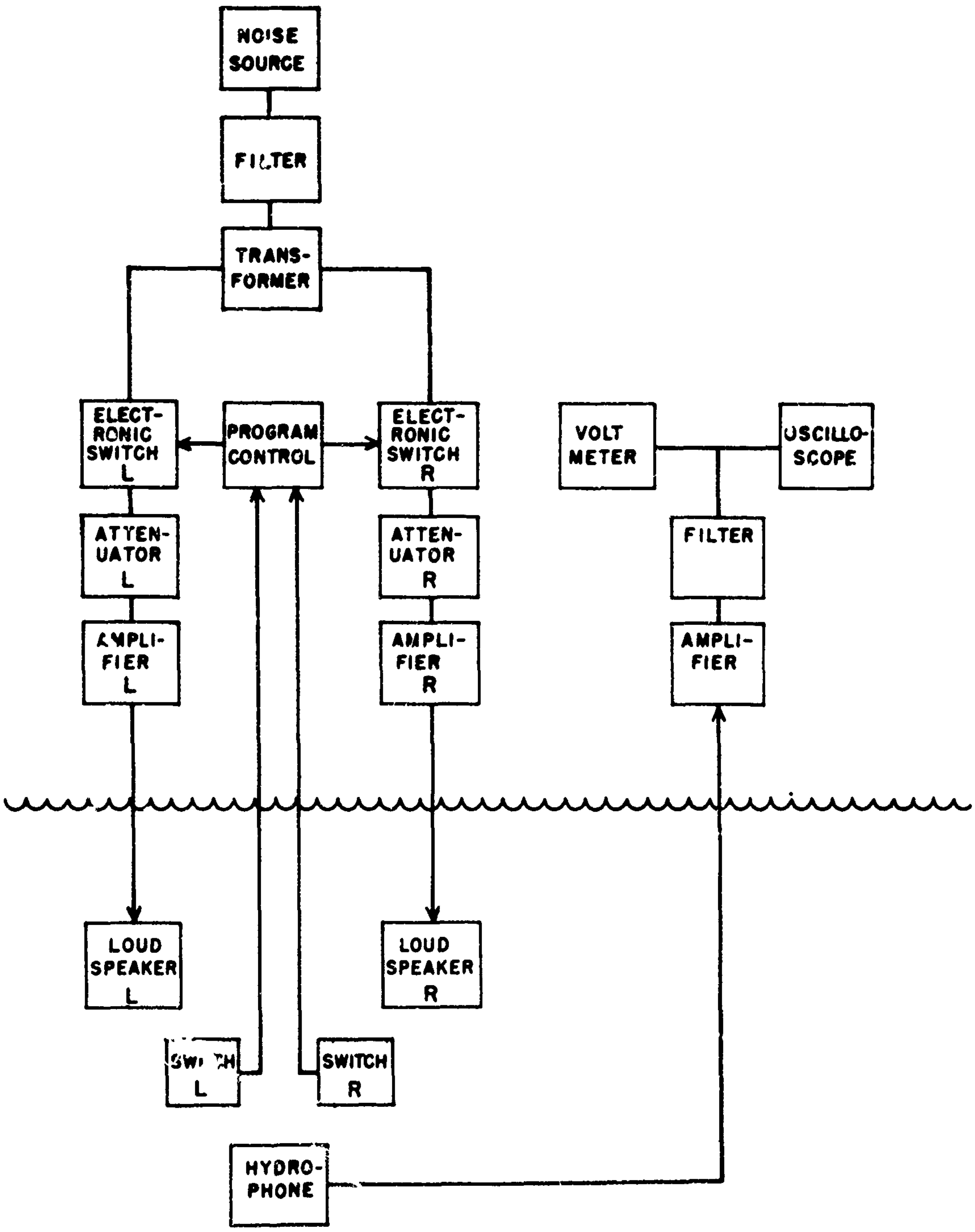

Fig. 1. Block Diagram of Experimental Apparatus for Experiment 1.

located approximately at the diver's station was used to monitor the experiment and for calibration purposes. Signals from this hydrophone were voltage amplified by a Massa model M-185 amplifier, filtered by a Dynatronics model 720 or an Allison model 2BR band pass filter and displayed on a Ballantine model 643 vacuum tube voltmeter and a Tektronix type R564B storage oscilloscope. All electronic equipment was housed in the NAVSUBMED RSCHLAB Mobile Psychoacoustics Laboratory,[13] which was also used for preliminary testing.

Test Environment. The experiment was conducted at the north end of a pier at the Narragansett Bay Campus of the University of Rhode Island. Water depth varied from about 15 to 20 feet depending on tidal stage. The bottom was sand and gravel covered by a layer of silt and was littered with clam shells and debris consisting of old pilings, bottles, etc. Fairly strong currents occurred as the tide ebbed, but currents were negligible at all other times. The location is exposed to all but westerly winds. Rough water, due to weather conditions, frequently caused postponement of scheduled test sessions. The water in the vicinity of the pier is quite turbid with visibility ranging up to a maximum of about six feet. At the beginning of this experiment, water temperature was about 55-57° F.

Ambient noise level varied somewhat with weather conditions. On a windier than normal day (wind speeds 20-30 kts) the ambient spectrum level was observed to be -2 dB re 1 μbar in the vicinity of 1 kHz. On calmer days, the level fell slightly, but was generally in excess of -7 dB spectrum level. This level apparently was due in part to surf breaking on the nearby gravel shore, local traffic, and pumps and other machinery being operated on the pier.

Stimuli. For the first two test sessions of the first experiment, the signal used was a broad band noise with a spectrum level of 3.5 dB re 1 μbar. Thus, the signal-to-ambient-noise level in the vicinity of 1 kHz varied from about 5.5 dB to 10.5 dB. Levels were not measured at other frequencies. This signal was difficult for the divers to hear.

For the last two sessions of the first experiment, the signal was a band limited noise having a center frequency of 1 kHz and a band width of 46 Hz. This signal had a spectrum level of 17 dB re 1 μbar yielding signal-to-noise ratios of 19 to 24 dB and was clearly audible above the ambient noise to all divers when breath-holding.

The stimulus was a repetitive pair of the noise bursts described above, one burst from each speaker. The signals had rise/fall times of 10 msec, and were on for 200 msec with a 150 msec silent interval between the two bursts of a pair. A 500 msec interval separated the pairs of bursts. Thus, the diver heard a repeating pattern approximating musical waltz time.

Procedure. In the first experiment four divers were tested individually in each of four sessions. However, the divers worked in pairs, there being two divers in the water at all times. One of these would be the subject, while the second stood by during each block. Between blocks the second diver made any

necessary changes in the separation of the J-9 loudspeakers in accordance with directions from a research assistant stationed on the pier.

The subject was instructed to indicate whether the first burst in the repeating stimulus pattern was coming from the left or the right of the second burst. He could take as long as he wished to make a decision. The pattern repeated until the diver responded by means of one or the other of the underwater switches.

Following a response, the stimulus pattern was interrupted for two seconds. During this interval the programming control system recorded the subject's response, determined whether the right or left speaker would be energized first for the next trial, performed the necessary switching and initiated the next trial.

The procedure was rehearsed with all divers in air in the Mobile Psychoacoustics Laboratory prior to the taking of data. This rehearsal followed audiometric testing of the subjects.

RESULTS

Experiment 1

Since the data were recorded in blocks of ten trials, one would expect that if a subject were responding strictly in accordance with chance, that is, by guessing, he would be expected to make up to 7 correct responses per block approximately 95% of the time. Eight or more correct responses could be expected 5% of the time and 9 or 10 correct choices could occur by chance on about one per cent of the blocks. The data presented in Tables I-III indicate whether the subjects attained 8 or more out of 10 correct responses (1) and could therefore be considered to be operating above chance level (at a 5% level of confidence) or whether his performance was more likely due to chance (0).

In the first session, each diver ran three blocks of ten trials each. Only one diver performed at better than chance level. All divers complained of difficulty in hearing the sound sources.

TABLE I

SESSION 1.

Block Angle	1 90°	2 90°	3 90°
Subject 1	0	0	0
Subject 2	0	0	0
Subject 3	0	0	0
Subject 4	1	1	1

TABLE IIA

SESSION 2.

A. Block Angle	1 90°	2 90°	3 90°
Subject 1	0	0	0
Subject 2	1	0	0
Subject 3	0	0	0
Subject 4	1	-	-

TABLE IIB

B. Block Angle	1 90°	2 60°	3 30°	4 15°
Subject 4.	1	1	1	0

TABLE III

ANGLE	90°	60°	45°	30°	15°
Diver 1	1	1	1	1	0
Diver 2	1	1	1	1	0
Diver 3	1	1	1	1	1
Diver 4	1	1	1	1	1

In the second session, during which conditions were identical to session 1, divers #1-3 still could not perform the discrimination,as is shown in Table IIA. Diver #4 performed quite well and his results are presented separately in Table IIB. He was able to discriminate between the sources until the angle was reduced to 15°.

Following sessions 1 and 2 all divers including diver #4 complained that one or both of the sound sources was very difficult to hear. Since the signal-to-noise ratio measured without the divers present was as low as 5 dB, it was expected the divers would only hear the signal while breath-holding. For the next two sessions, the bandwidth of the

signal was reduced to 46 Hz permitting the signal-to-noise ratio to be raised about 15 dB. Otherwise, the procedure was the same as for sessions 1 and 2.

The results of sessions 3 and 4 combined are presented in Table III. No diver had difficulty in discriminating the pattern for angles as small as 30°. At 15°, two divers were performing above chance level, two were not.

METHOD

Experiment 2

Subjects. The four subjects used in Experiment 1 and two additional subjects of similar background were used in the second experiment.

Apparatus. The underwater apparatus for the second experiment is schematized in Fig. 2. A dolly which held one J-9 transducer was mounted on a 20-foot long aluminum I beam. By means of a pulley arrangement operated from the pier, the J-9 could be positioned anywhere along the beam. The I beam formed the base of a right triangle with the J-9 position, as measured from the center of the I beam, defining the length of the base.

Directly below the center of the I beam, a Navy Underwater Systems Center scroll type XU-1210, hydrophone was mounted. A line from this position to the subject's position formed a right angle with the I beam and provided a visual reference for the subject. This line and a second imaginary line drawn from the observer to the J-9 defined an angle which could be continuously varied from 1.4° to about 35°. A rod mounted on the J-9 dolly broke the surface of the water and gave an indication of the position of the J-9 along a scale suspended parallel to the I beam but above the surface.

In general, the electronics employed were the same as for Experiment 1. The test environment was the same except that water temperature was about 52°F when this series began and about 48°F when the experiment was terminated. The stimulus was the same as for the last two sessions of Experiment 1 except that the standard signal (from the XU1210) always occurred first in the pattern and was at a spectrum level about 57 dB re 1 μbar. This signal enabled the divers to readily know when a trial began and ended, since it was clearly audible even above the diver's own bubble noise. The signal level from the J-9, however, was the same as for the last sessions of Experiment 1.

Procedure. From the point of view of the subject, the procedure for the second experiment was about the same as for the first. The trials were much more spaced out, since after each response an adjustment to the J-9 position would be made by the surface attendant. An attempt was made to obtain twenty trials in each session for each diver. In all, four sessions were run on each diver.

The subject was to indicate whether the comparison source (the J-9) was to the left or right of the louder standard source. Again, the subject could take as long as he wished to made a decision. The diver's response was signalled by light to the assistant on the pier who scored the response and then positioned the J-9 for the next trial.

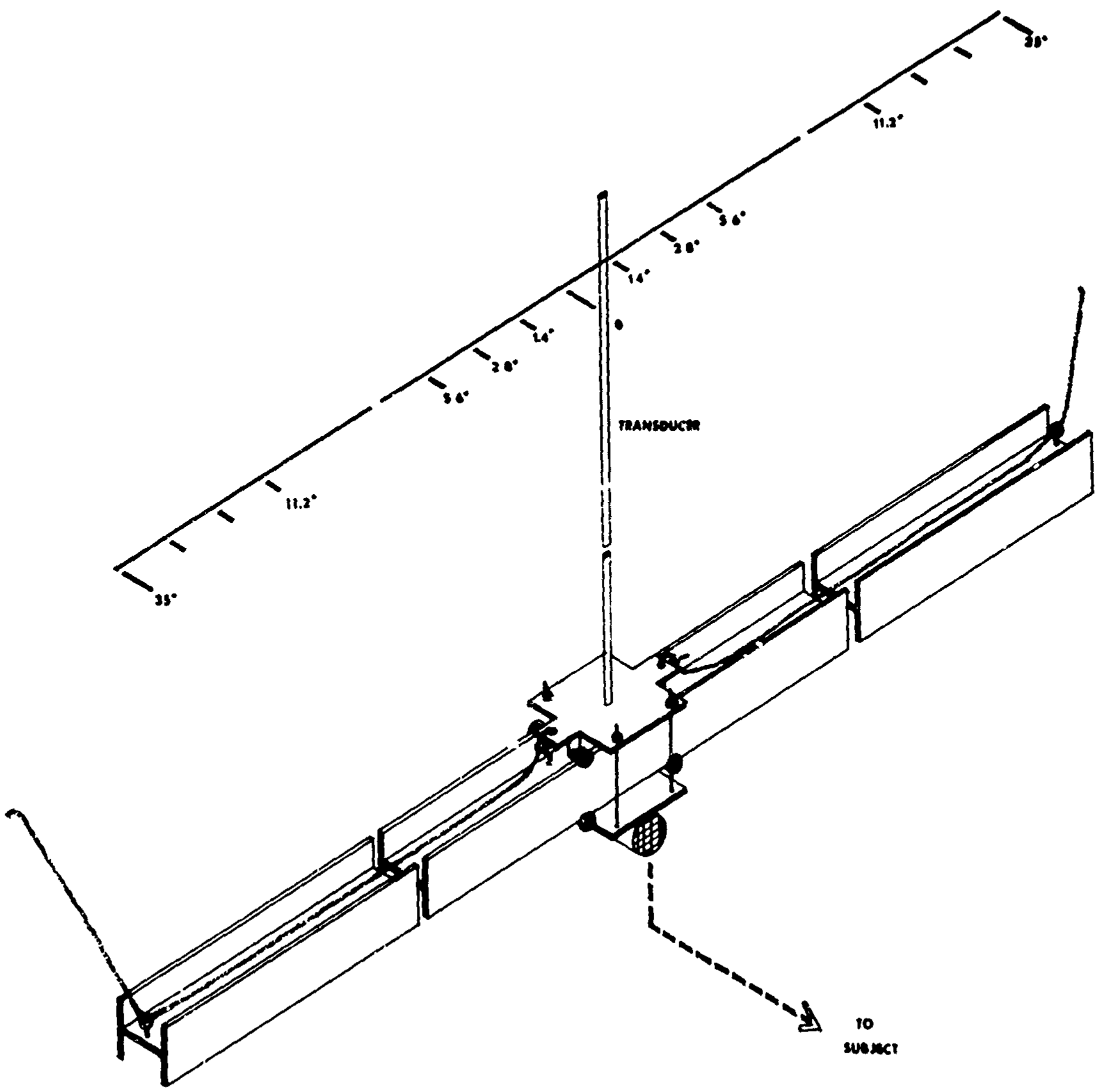

Fig. 2. Sketch of Movable Underwater Sound System for Experiment 2.

On any particular trial the position of the J-9 was determined in part by a prearranged schedule of left or right placement, and except for the first trial, by the correctness of the subject's previous response. If the subject reported the correct (left or right) position, the angle would be reduced for the next trial. If the subject made an error, the angle was increased. In this way most of the data would be obtained in the region between certainty and just change performance - that region wherein lies the minimum audible angle. The first trial

always started with an angle large enough to be clearly discriminated by the subjects.

RESULTS

Experiment 2

Because of the procedure used in collecting these data, it is not possible to draw a psychometric function for underwater localization. However, an estimate of the minimum audible angle was usually obtained for each session for all divers.

The results for one diver had to be eliminated since he adopted an unfortunate response pattern that rendered his data uninterpretable. Most of his responses consisted of "left" responses. Consequently, when the correct response was "right" he was almost invariably wrong and when the correct response was "left" he was invariably correct. The data for the remaining five divers are shown in Table IV along with the means across trials for each diver, the means across divers for each trial, and the grand mean.

The means across trials for each diver range from 2.7° to 8.55° with an overall mean of 5.25°. The twenty estimates of the minimum audible angle, on which the grand mean is based, range from 1.4° to 11.3° and has a fairly symetrical distribution with a median and mode of 5.7°.

The means across divers (for sessions) show no particular trend except that the mean for session 4 is somewhat smaller than the means for sessions 1

TABLE IV. Estimated minimum audible angles in degrees for five divers over four test sessions

DIVERS	SESSION 1	2	3	4		MEAN ACROSS TRIALS
2	5.7	2.1	8.6	2.1		4.63
3	5.7	2.1	1.5	1.5		2.70
4	5.7	5.7	2.9	1.4		3.93
5	2.9	8.6	5.7	8.6		6.45
6	8.6	8.6	11.3	5.7		8.55
MEAN ACROSS DIVERS	5.72	5.42	6.00	3.86	GRAND MEAN	5.25

through 3. However, this difference is not statistically significant.

DISCUSSION

In Experiment 1, the apparent improvement in performance for all divers for sessions 3 and 4, as compared to sessions 1 and 2, is interesting. Norman, et al.[14] suggested that weak underwater signals may be perceptible but not localizable because of possible differences in the sensitivities of bone conduction and tympanic conduction pathways through which acoustic energy may reach the cochlea. The dual path hypothesis originated with Sivian[15,16] who argued that underwater sound may be heard through the normal ear canal - middle ear route (the tympanic route), but, because of the impedance mismatch between the water and the ear, with a reduction in sensitivity. Sivian calculated that this reduction would be about 40 dB at 1 kHz. He also calculated that an underwater sound pressure level about 3 dB higher than that required for underwater eardrum hearing would be sufficient to drive the mastoid process at an amplitude equivalent to the BC threshold in air resulting in underwater hearing via a bone conduction route.

This line of reasoning lay behind Ide's[9] development of a diving helmet consisting in part of a 4" wide strip of sponge rubber running mid-sagitally from the forehead to the back of the skull. The helmet was supposed to damp the BC pathway to the cochlea thereby "unmasking" the eardrum route with a consequent enhancement of the underwater binaural effect. The use of this helmet did enhance the underwater localization ability of some divers. Norman found that neoprene patches over the ears of an otherwise bareheaded diver markedly reduced the accuracy of underwater auditory localization from that obtained from completely bareheaded or completely hooded divers, although these same patches had little effect on hearing sensitivity. This finding complements Ide's findings and lends further support to Sivian's dual path hypothesis.

Our data cannot confirm Norman's suggestion of audible but nonlocalizable (weak) signals since, in addition to changes in signal bandwidth as well as level, there also very likely were some experiential factors operating for which we did not control. It is more likely that the poor performance of most divers in sessions 1 and 2 was due to their inability to hear both stimuli on several trials.

Andersen and Christensen[17] have shown that, for a gross underwater localization task (similar to our Experiment 1), performance in free-field conditions differs little from performance in reverberant conditions.

The results of Experiment 2 are comparable to Feinstein's white noise data. (Feinstein's mean: 7.3° our mean: 5.25°.) Such discrepancies as may exist are likely due to differences in experimental procedure. It seems clear that provided the signal-to-noise ratio is sufficiently large, underwater auditory localization is at least as good in a noisy and reverberant environment as it is for the relatively quiet and anechoic conditions used by Feinstein.

It is interesting that our mean underwater m.a.a. of 5.25° is just about

4 1/2 times the m.a.a. found in air at 1 kHz.[18] Since the speed of sound in water is about 4 1/2 times the speed of sound in air, time of arrival and phase differences would differ in the two media by about the same factor. On this basis it is tempting to infer that the same mechanisms for auditory localization operate in the two media. Feinstein found the underwater m.a.a. at 3.5 and 6.5 kHz to be about 11.5°. This figure is perhaps a bit larger than one would expect from Mills' data, (multiplied by 4 1/2). In the frequency range above 2-3 kHz the m.a.a. in air is believed to be determined by intensity differences at the two ears caused by diffraction effects of the head on the sound field. However, in water, comparable diffraction effects perhaps do not occur for bareheaded divers. For hooded divers, diffraction effects probably occur at frequencies 4 1/2 times those in air. The fact of the matter is that insufficient empirical information concerning the acoustic properties of the human head in water is available at this time to permit easy comparisons between localization phenomena in air and under water.

To complicate matters, Feinstein's data and our own were obtained with divers wearing hoods. Whereas the head acts as a rigid obstacle in a sound field in air, the diver's hood, perhaps, acts instead as a pressure release device in water. Furthermore, the possible influences of other items of divers' equipment, especially face masks, on underwater hearing phenomena have not been investigated. In short, data currently available are of little use in establishing or testing hypotheses or models of underwater auditory localization.

CONCLUSIONS

We conclude that, provided the signal-to-noise ratio is sufficiently large, divers can perform auditory localization tasks with considerable precision without any sort of listening aid. This ability is not severely impaired, if impaired at all, in comparison to Feinstein's data, in noisy and reverberant listening environments.

The cues utilized for underwater auditory localization are not understood at this time. It appears that further research, oriented towards specifying optimal signal configurations for underwater acoustic navigation systems, could be profitably pursued. No underwater investigations have yet been conducted on vertical plane auditory localization, auditory depth perception, or the role of body orientation on localization phenomena. Research on these and other aspects of acoustic orientation are needed in order to specify optimum signal characteristics for practical underwater acoustic orientation systems for Navy divers.

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